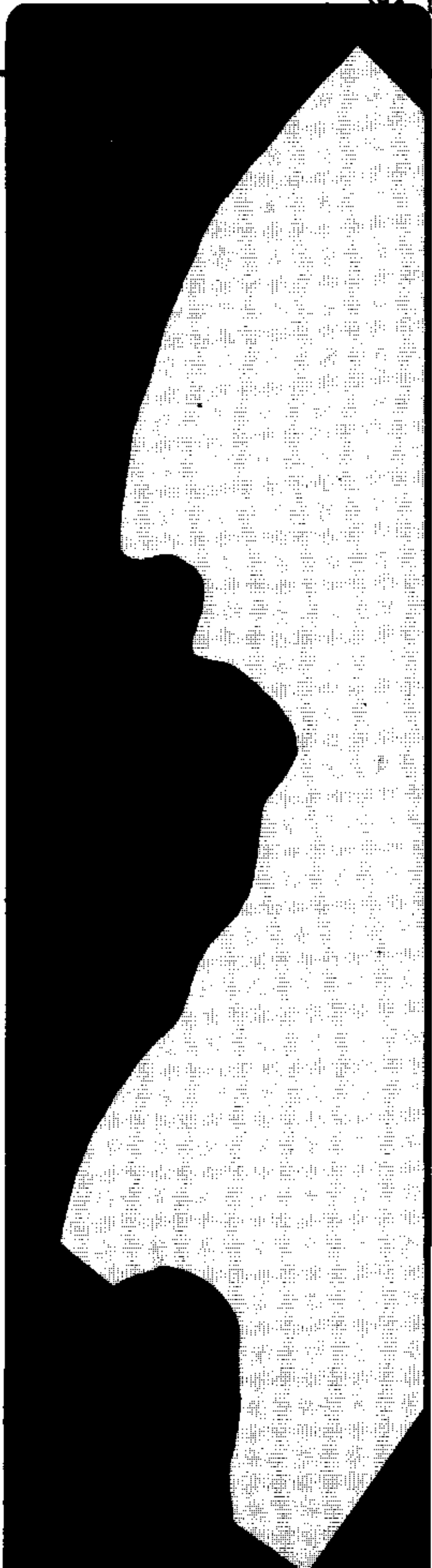

Great Lakes Coastal Geology

The Sediment Problem at Twelvemile Creek Inlet Lake Ontario, Wilson, New York

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THE SEDIMENT PROBLEM AT TWELVEMILE CREEK INLET
LAKE ONTARIO, WILSON, NEW YORK

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ABSTRACT

An active gravel barrier dominates the mouth of the West Branch of Twelvemile Creek, Wilson, NY. Under natural conditions this barrier builds up to separate completely the estuary of the creek from Lake Ontario. To keep the creek open, the Town of Wilson has supported costly dredging operations for the past 20 years. Monitoring the effects of various wave and shoreline processes provides the geologic information necessary to determine how the town can solve this problem.

Studies of wind and wave patterns, sediment size and distribution, and a flourescent tracer study show that most of this sediment is composed of the red fine-grained sandstones and shales of the locally exposed Queenston Formation. Storm waves induced by high winds and aided by above average lake levels encourage erosion and accelerate sediment accumulation at the inlet. Easterly moving longshore currents account for nearly all of the 12,805 m^3 (16,749 yd^3) of sediment removed by dredging between April 1977 and June 1978.

From our study, we conclude that a jetty constructed off the west bank of the creek extending lakeward into the breaker zone would both trap sediment entering the inlet as longshore drift and would retard bluff erosion, thus cutting off two major sediment sources.

INTRODUCTION

Under natural conditions, a barrier of sediment periodically builds up across the mouth of the West Branch of Twelvemile Creek, Wilson, NY, Lake Ontario, preventing passage of small pleasure craft between the creek and Lake Ontario. The barrier is formed by the junction of two spits. Approximately 12,615 m^3 (16,500 yd^3) of sediment had to be dredged from the creek mouth in one year. To keep the creek open, for 20 years the Town of Wilson has supported costly dredging operations of accumulated sediment (D. Stewart, personal communication, 1977).

With the hope of finding a solution to this problem, we set out to determine the cause of sediment buildup at the mouth and along the adjoining shoreline of the West Branch of the creek. Winds, waves, currents, lake level fluctuations, as well as coastal sediment and other phenomena, interact to determine the way the shoreline and spits appear. By studying the effects of various combinations of these processes we were able to determine what measures should be taken to solve the problems of sediment buildup.

GEOLOGIC SETTING

General

The bedrock underlying the western end of Lake Ontario consists of interbedded fine-grained red sandstone, mudstone, and shale of the Queenston Formation (Kindle and Taylor 1913; Fisher 1977). It does not crop out in the study area, but forms portions of the banks along Twelvemile Creek.

Glacial drift of late Wisconsin age overlies bedrock throughout the area. The lowest unit exposed in the study area consists of a compact, purple-gray sand-silt-clay till of variable thickness. It contains approximately 5 percent pebbles and cobbles. The percentage of pebbles and cobbles decreases upward toward the top of the till layer where numerous lenses of tan and/or gray sand-silt-clay form an upper "waterlaid" till facies (Calkin, Drexhage, and Brennan 1978; Driemanis 1976). Throughout the study area, the till is overlaid by 0.3 to 0.5 m (1 to 2 ft) of red-brown silts that are similar to those of glacial Lake Iroquois (Calkin and Brett 1978).

For the purpose of description, we divided the study area into three physiographic sections: the Western, Central, and Eastern reaches (Figure 1). We collected samples of the nearshore, beach, and bluff environments for lithologic and textural analysis. By knowing what materials comprise each section we can determine the source of the sediment. The clogging of the inlet is caused by the mixing and redistribution of these materials.

Most of the field work for this study was undertaken between April 1977 and June 1978.

Central Reach

The Central Reach is the area of greatest concern in this study. It includes the entire area surrounding the mouth of the West Branch of Twelvemile Creek (Figure 1). Two hooked spits are formed across the mouth of the creek in opposing directions. The spits respond to the various wave conditions with growth and depletion (King and McCullagh 1971).

West Spit

We studied in greater detail the spit extending from the west bank because it responds to wave action and is, therefore, the more active of the two. The size of the sediment across the spit varies considerably; the coarsest material is along the lakeward side forming a steep beach face (Figure 2). It consists of rounded cobbles generally greater than 64 mm (2.5 in) in diameter. Due to its position, the coarse sediment provides some protection from most wave attack for the finer-grained areas of the spit.

As we move inland toward the axis of the spit, sediment size decreases. The land portion of the spit consists of medium to very coarse sand. The "hooks" of the spit are composed of a coarser material similar to the beaches of the western reach. The back or estuarine shoreline of the spit is flanked by silts derived from the quiet and inactive waters of the creek.

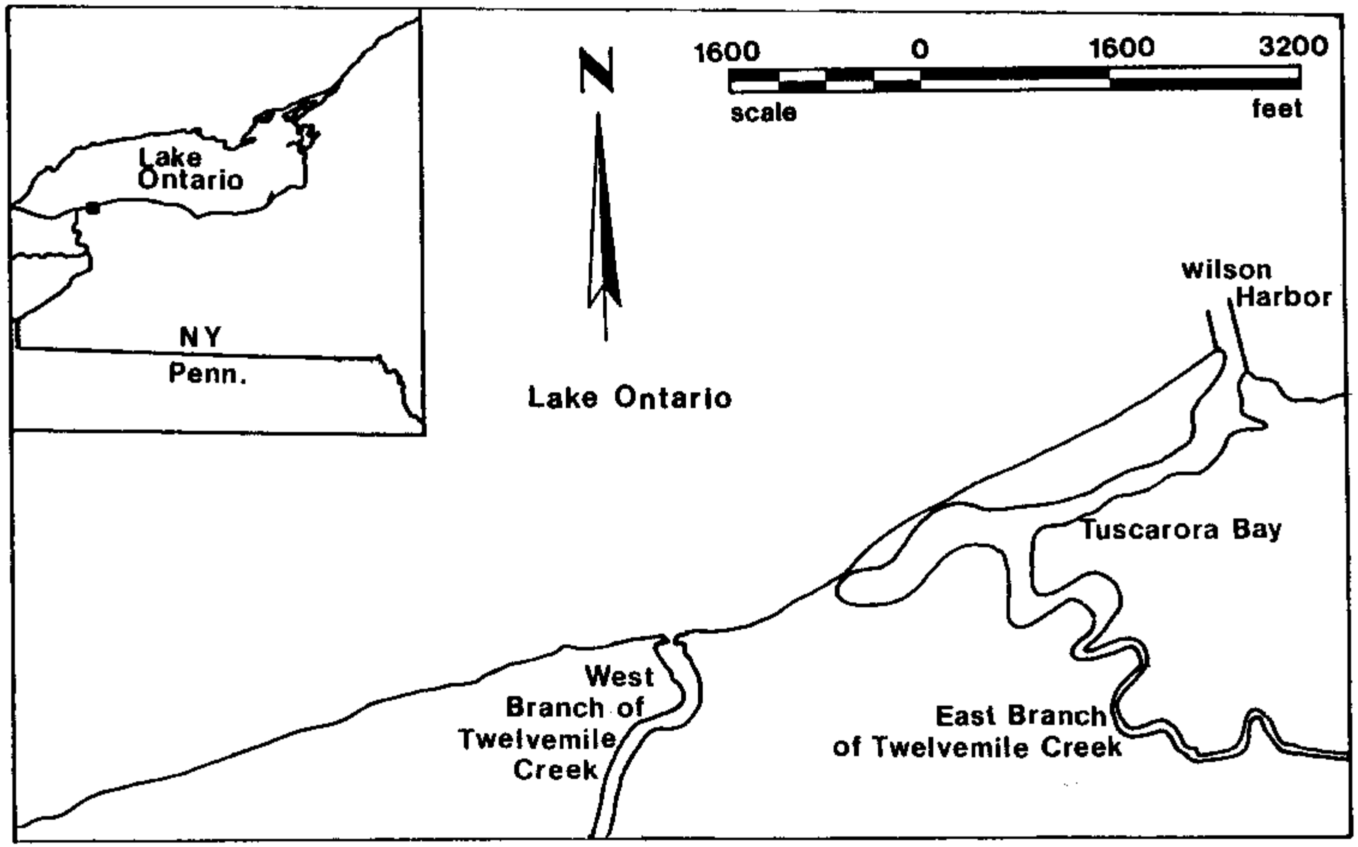

Figure 1 Study Area

East Spit

The spit that extends from the east bank remained stationary throughout the period of investigation. This raises the possibility that the spit is in equalibrium with the interacting nearshore wave and current processes. The east spit is composed almost exclusively of coarse sand and gravel, except along the beach face where there is a small berm of pebbles.

There is a small submerged sand bar fluctuating around the mouth of the inlet. It generally occupies an area 7 to 11 m (23 to 36 ft) from shore in the immediate vicinity of the breaking waves. This bar accumulates enough sand to endanger pleasure craft.

Western Reach

The coastal zone extending 1.6 km (1 mi) west of the West Branch of the Twelvemile Creek inlet (Figure 1) is characterized by high, unstable bluffs and by narrow, steep coarse-gravel beaches.

The bluff heights average 5.8 m (19 ft); these bluffs are composed of the purple-gray till overlaid by 0.5 m (2 ft) of red-brown Lake Iroquois lacustrine sediments. The bluffs are steep and undergo constant slumping, especially after rain.

The narrow beach at the toe of the bluffs ranges from 0.5 to 2.0 m (1.6 to 6.6 ft) wide and slopes 18°. The beach is composed of rounded cobbles and pebbles greater than 4 mm (0.15 in) in diameter, predominantly of red sandstone and shale, white to buff limestones, and some gray sandstones. About 13 percent of the sediment consists of rounded igneous and metamorphic stones foreign to the area and available only from the bluffs. This coarse sediment extends out from the beach to the breaker zone about 15 to 17 m (49 to 56 ft) from shore, with only intermittent patches of sand.

The only protective structures along the Western Reach, at the time of this study, were a small expanse of boulder-sized crushed rock, known as riprap emplaced at the toe of the bluff, and another bluff structure built of cement about 31 m (102 ft) long.

Eastern Reach

The Eastern Reach extends 1.4 km (0.9 mi) east of the West Branch of Twelvemile Creek to the jetties at Wilson Harbor (Figure 1). One of only three sand beaches located along the Lake Ontario shoreline of Niagara County occurs in this reach (Drexhage and Calkin, in press).

The western third of this reach is characterized by a broad beach area, part of the Tuscarora State Park (US Army Corps of Engineers 1942). The beach averages about 4 m (3 ft) in width and slopes gently 14 cm/m (1.7 in/ft). The composition of the nearshore region is similar to the beach with intermittent patches of cobbles and pebbles. Behind the beach is a region of sparsely vegetated sand dunes generally 0.6 m (2 ft) high. The dune area extends about 3 m (10 ft) to the toe of the gently sloping, well-vegetated bluffs. These

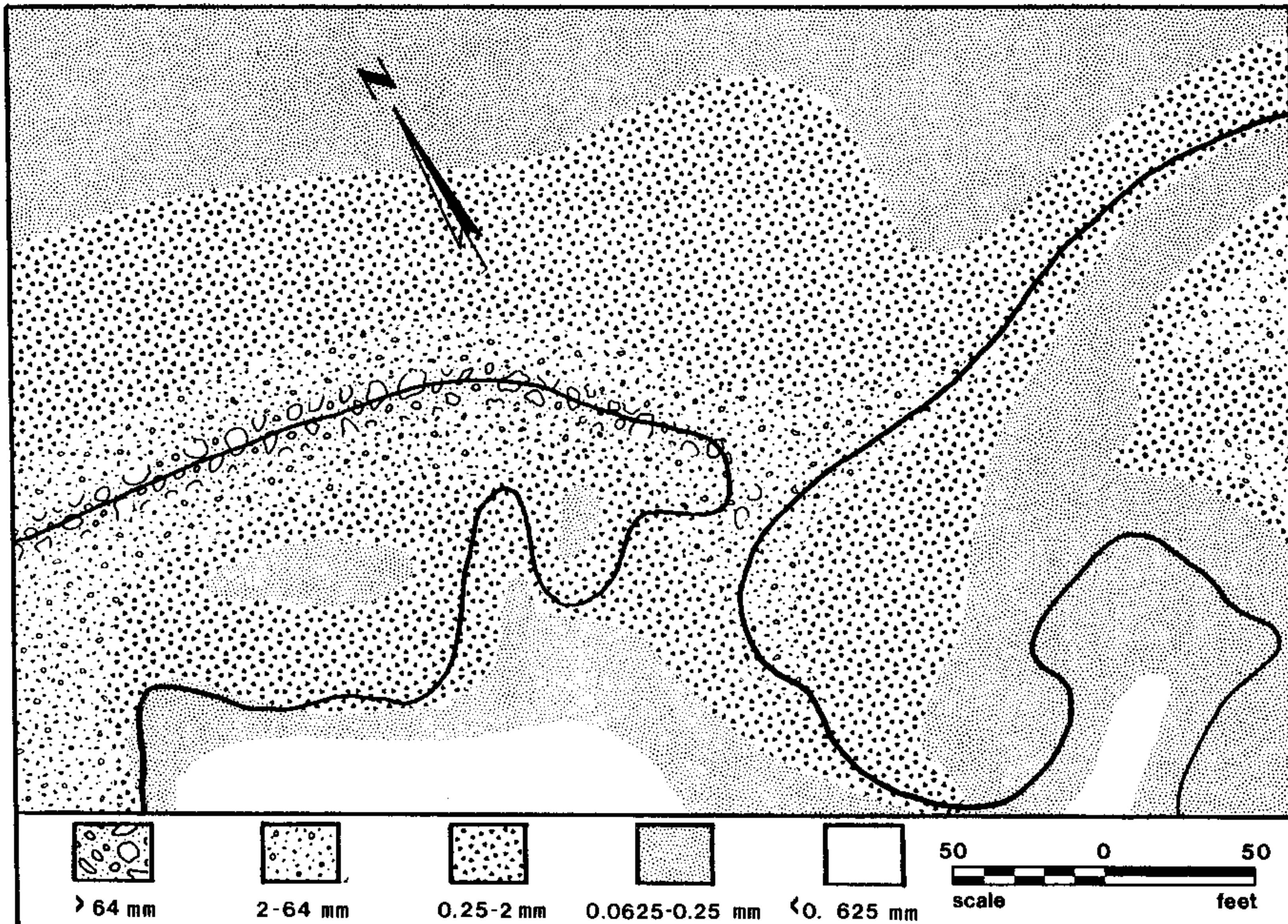

Figure 2 Textural Map of Study Area (Central Reach)

bluffs are similar in composition to those of the Western Reach. They reach heights of 3 to 5 m (10 to 16 ft).

East of the Tuscarora State Park beach area the coast becomes a steeply bluffed peninsula of till and Lake Iroquois sediments and is known as The Island. The Island is separated from the main coast by the East Branch of Twelvemile Creek (Figure 1). The lakeward bluffs are protected from wave attack by sheet metal pilings that obscure the lower 4 m (13 ft) of the bluffs. The nearshore region of this area is similar to the nearshore area of the Western Reach.

Just west of the jetties at Wilson Harbor is a beach of medium-to-fine sand derived from the easterly moving longshore drift.

West Branch of Twelvemile Creek

Another distinct physiographic region critical to this study is the basin of the West Branch of Twelvemile Creek. Sediment from this area eventually empties into Lake Ontario and becomes part of the littoral process.

The headwaters of the creek are located 15.3 km (9.5 mi) south of the mouth at the foot of the Niagara Escarpment. The stream bed cuts into Queenston shale bedrock and incorporates this rock and the overlying glacial till into its stream load. The percentage of exposed bedrock versus drift forming the banks decreases northward from the escarpment to Lake Ontario.

Waters of the West Branch of Twelvemile Creek flow entirely through agricultural and wooded areas, carrying relatively small amounts of sediment in suspension. Heavy mineral studies undertaken as part of this work, following the methods of Rittenhouse (1943, 1944), demonstate that this load is evenly distributed among the adjoining tributaries.

Sediment begins to be deposited in the quiet waters of the creek about 3 km (1.9 mi) upstream from the river mouth. Within the estuary, an area where river waters meets lake waters, the creek suspends over 10 times more sediment than it does at the headwaters. Therefore, the creek bed of the estuary consists of very loosely compacted, organic silt with an average diameter of 0.004 mm (0.0002 in).

The West Branch of Twelvemile Creek had a discharge rate of 0.16 m^3/sec (5.78 ft^3/sec) measured at the mouth of the river 8 April 1978. This figure increases and decreases in response to precipitation, temperature, vegetation, terrain, surficial features, land use, and geology. Results of monthly discharge rates indicate that this, an intermediate-sized basin has lower discharge rates than similar sized rivers (Buxton 1977).

PROCESSES AFFECTING THE COAST

Wind and Wave Climate

The wave climate at a given shoreline depends on the offshore, deepwater waves. These waves are controlled by the duration and intensity of winds and storms from various directions, the fetch or distance the wind travels across open waters (Figure 3), and the bottom topography (Coastal Engineering Research Center 1973).

The wind and wave measurements for this study were taken from the west spit and from the weather records of the Niagara Coast Guard Station at Youngstown, NY, 17.7 km (11 mi) to the west. Prevailing winds in the study area are from the south to southwest; however, during the study period (April 1977 to June 1978), the majority of storm velocity winds occurred from the northeast. Storms from the northeast have greater fetch distances than those from any other direction (Figure 3), and although the fetch is not as important as the prevailing wind in wave generation, the combination of a long fetch with storm velocity winds can be disastrous (Komar 1976). This results in higher storm surges and greater waves. Because of the location of the site relative to open water, winds occurring from other directions appear not to have a significant long-term effect on the shoreline configuration of the study area.

The increase in water level by surges is a significant factor in sediment transport. With a higher water level, waves can attack a greater range of elevations on the beach and bluffs. Also, higher waves break farther offshore, widening the surf zone and setting more sediment in motion.

Offshore winds, which in this case are the prevailing winds, induce an offshore surface current that causes a bottom current close to the shore. This may aid in transporting sediment landward (Coastal Engineering Research Center 1973).

As waves travel from deep water into shallow water (or more specifically, into water having a depth that is one-half the deep water wavelength), they feel bottom and change height and direction. Wave crests begin to follow the bottom contours. The change in direction of different parts of the wave results in convergence or divergence of wave energy along the shoreline. Where waves converge, the wave energy dissipates causing sediment depletion or erosion. Wave orthogonals (wave paths) converge slightly at the bluffs to the west in all cases, indicating that erosive processes are occurring continuously there. Areas where orthogonals diverge are those of very low energy, causing sediment to build up. This is what occurs directly at the mouth of the West Branch of Twelvemile Creek.

Longshore Currents

Much of the sediment deposited in the inlet at Twelvemile Creek is carried in as longshore drift. Wave crests usually break at a slight angle to the shoreline, which causes a current to run along the shore.

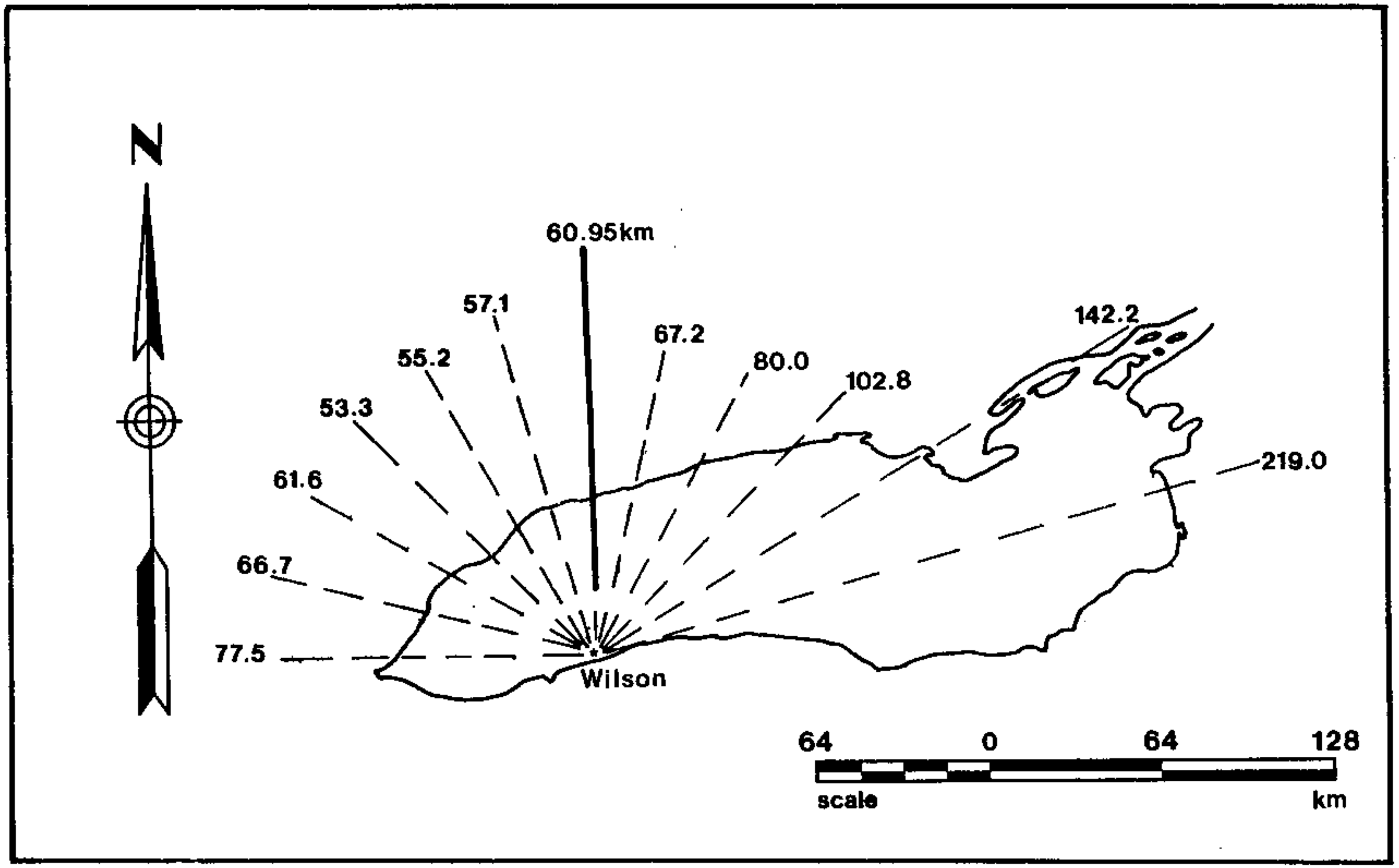

Figure 3 Fetch Distances Across Lake Ontario for Wilson, NY

Longshore currents can travel in either direction along the shoreline, depending upon the wind direction. If the currents travel in a single direction most of the time, there will be a net movement of sediment in this direction. During the study period, waves approached the shoreline at the West Branch of Twelvemile Creek from the northwest 65 percent of the time, resulting in net transport from west to east. These predominant easterly moving longshore currents are well expressed in satellite photographs of Lake Ontario (Pluhowski 1975). Waves approached from the northeast 27 percent of the time, temporarily reversing the longshore transport. During the remaining 8 percent of the time, waves approached perpendicular to the shoreline. Sediment under these conditions moves back and forth with the passing wave motion, without net movement in either direction (Johnson 1956; Goldsmith and Colonell 1970).

Creek Flow

Currents caused by the discharge of Twelvemile Creek act as concentrated jets of water carried lakeward through the breaker zone, similar to rip currents. When the discharge rate of the creek equals the velocity of the approaching waves, a standing wave phenomenon occurs at the mouth of the inlet (Figure 4). In this case, the waves move neither toward nor away from the shore, but appear to rise and fall in the same place. This phenomenon was seen frequently throughout the study period. The standing waves interfere with the processes of longshore transport and help trap the sediment normally carried as longshore drift.

The velocity of a stream is directly related to its ability to transport sediment: if a stream has a high velocity, it can transport larger sediment particles; but a low velocity, sluggish stream can carry only finer particles. The velocity of the West Branch of Twelvemile Creek is low in comparison with other streams of western New York (Harding and Gilbert 1968; Buxton 1977), and only during periods of high discharge, as in flooding, will the velocity be sufficient to transport pebbles and cobbles from bed and bank deposits any significant distance toward Lake Ontario. In the meantime, these coarse materials rest on the streambed making up 83 percent (by volume) of material along the entire creek length.

At the estuary, the channel widens and velocities drop drastically. Clay and silt, contributed to the stream from the whole drainage basin, travel downstream to the estuary, where they eventually settle. In the estuary, only 11 percent of the bed material is of pebble size or larger, and none of this can be moved during the normal, sluggish stream flow.

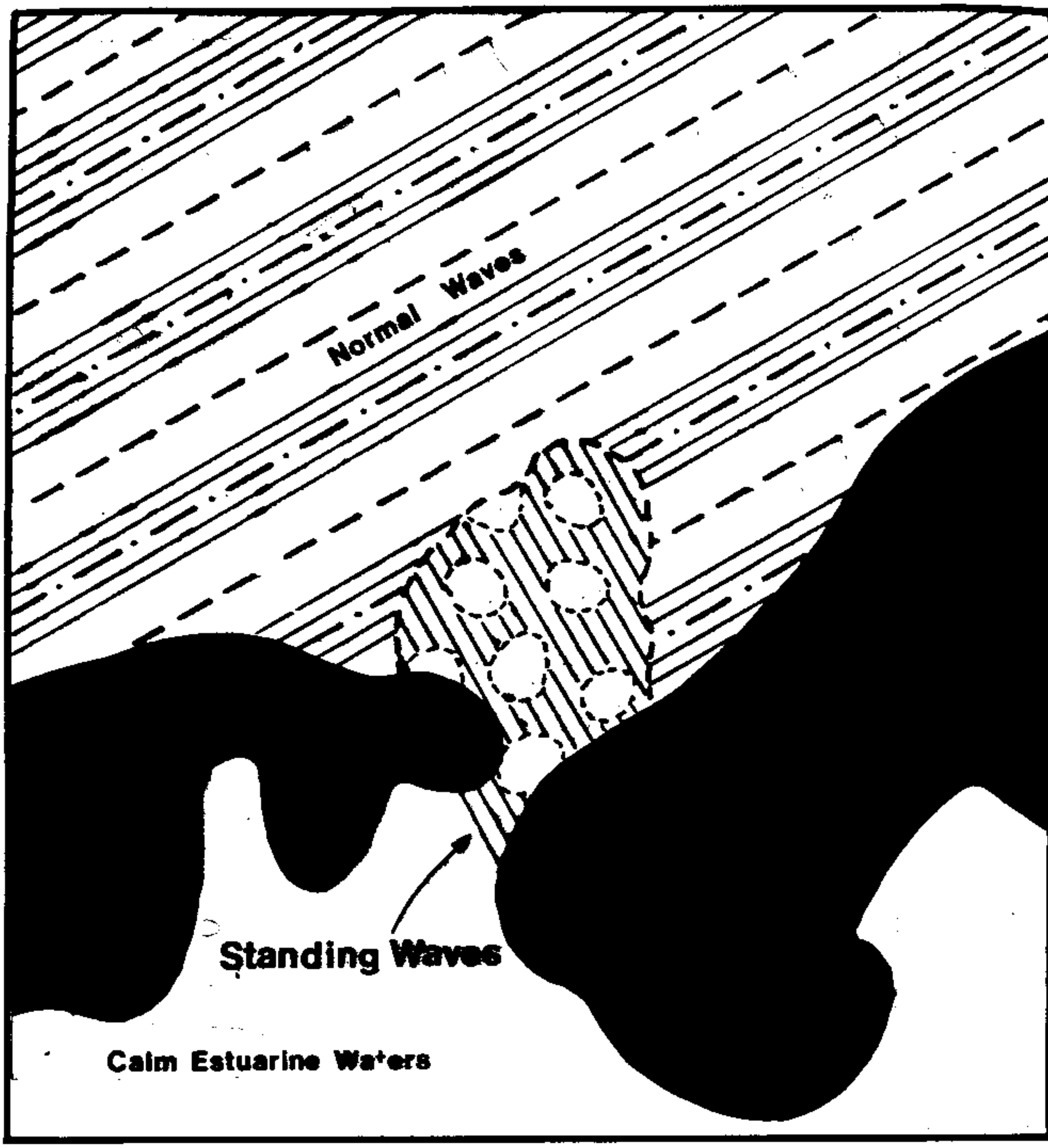

Figure 4 Standing Wave Phenomena Occurring at Mouth of Inlet

Lake Level Fluctuations

Lake Ontario experiences the greatest range of lake level fluctuations of all the Great Lakes (Great Lakes Basin Commission 1975). These fluctuations have a significant effect on the coastal recession of the area, as higher levels allow a greater range and expanse of active erosion (Davis, Siebel, and Fox 1973).

Lake levels do not vary greatly as the result of tides. However, they are subject to seasonal and annual hydrological changes in water level and to water level changes caused by storm surge, barometric pressure variations, and seiches (Coastal Engineering Research Center 1973; Hutchinson 1975). Also, Lake Ontario is subject to occasional water level changes by regulatory works.

Seasonal fluctuations appear to be the most consistent of all the major water changes (Figure 5). During each year, the water falls to its lowest levels during the winter and rises to its highest levels during the summer.

Short periods of fluctuation on Lake Ontario are produced by storm surge followed by seiche activity (Coastal Engineering Research Center 1973). Storm surge occurs when winds passing over the lake raise the water level at one end and lower it at the other. Changes in the water level depend upon the fetch across the lake and the average depth of water. For this reason, it is easy to see why northeast winds, which have the longest fetch distances, also have the greatest effect on the coastline at Wilson.

Maximum short-period fluctuations, which can last from a few minutes to several hours on Lake Ontario, were measured at Olcott, NY, during the period of gage record (1933 to 1971). They show a rise of 1.3 m (4.2 ft) above mean surface elevation (MSE), and a fall of 1.2 m (3.8 ft) below MSE.

Ice Formations

Winter severity affects the ice conditions of Lake Ontario. The lake is never completely frozen over. However, during most winters (25% of each year) extensive stretches of icefoot (Hutchinson 1975) form along the Lake Ontario coastline. During this period, all of the usual coastline processes causing erosion or buildup of the shoreline cease.

A large icefoot, stretching 9.1 to 12.2 m (30 to 40 ft) lakeward and 0.6 to 0.9 m (2 to 3 ft) above the water surface, formed along the Wilson coastal area in a two- to three-week period of subfreezing temperatures beginning December 9. Waves forced small fragments of lake ice into shallow coastal waters where they became compacted and welded to the shoreline. The icefoot grew continuously lakeward with the persistent action of storm waves heaping up ice along the lakeward edge until 7 January 1978, when it stretched 23 m (75 ft) from the shoreline and 1 to 1.5 m (3 to 5 ft) above the water surface. Much offshore and beach sediment is mixed in with the ice layers of the icefoot and thrown onto the ice surface by the breaking waves.

The inlet area of Twelvemile Creek, the part affected by Lake Ontario, was completely frozen over between 17 December and 5 March 1977-78. However,

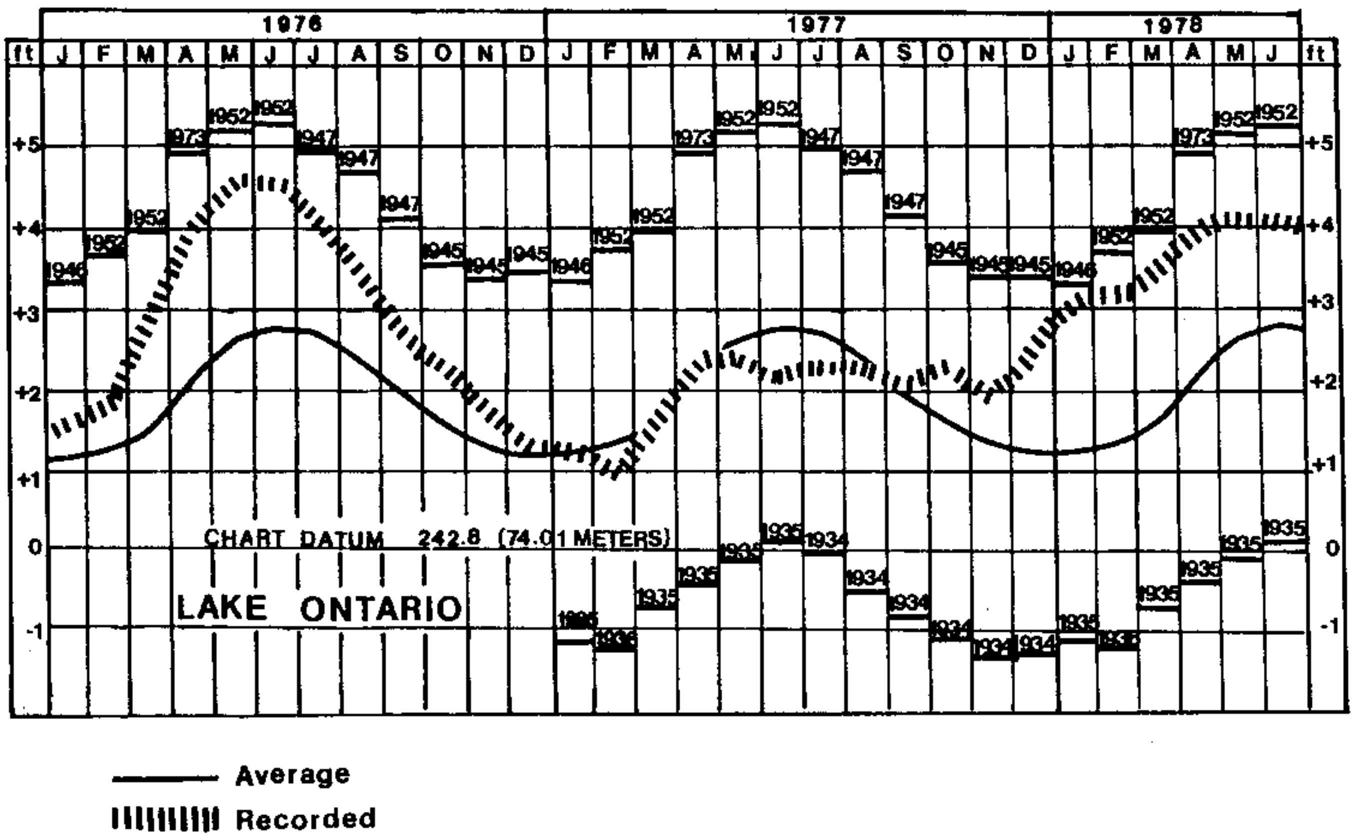

Figure 5 Annual (Seasonal) Hydrological Cycle for Lake Ontario

Source: NOAA 1978

the water in the immediate inlet area remained unfrozen, though filled with small ice fragments. Only once during the winter did the inlet become completely icebound. This occurred during a period of still lake conditions on 26 and 27 February. The ice completely disappeared from the coast between 9 and 17 April 1978.

While some erosion occurs as a result of ice contact with the bluffs, the icefoot protects the coastline from the strong wave attack and consequent erosion during the winter and spring. Since the unfrozen immediate inlet area was the only region exposed to the high energy of winter wave attack, the possibility of sediment buildup there was reduced greatly.

Comparison shallow water surveys made prior to ice formation on 30 November 1977 and immediately after the icefoot had disappeared on 17 April 1978, show that little erosion or sediment accumulation had taken place in the inlet area during this period and that the shoreline configuration had not changed. Therefore, it is probable that little movement of beach-sized material had occurred along the bluffs or beaches nearby. However, icefoot formation and breakup are known to play an important part in the modification of offshore topography and to aggravate shoreline erosion elsewhere on the Great Lakes (Siebel, Carlson, and Maresca 1975; Marsh, Marsh, and Dozier 1973). More detailed study is needed to determine the long-term effects at Wilson.

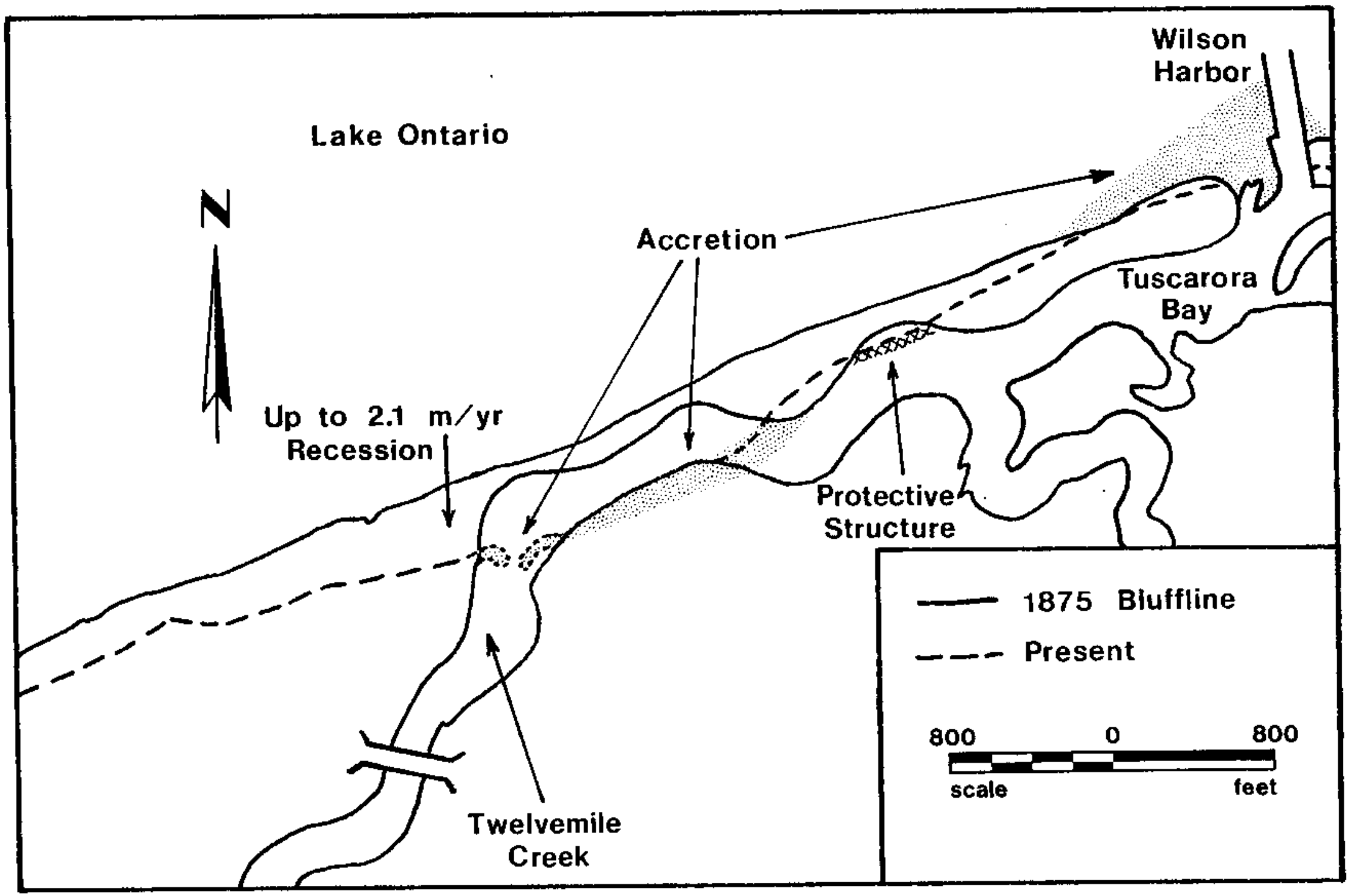

Figure 6 Historic Bluffline Changes

Source: Lake survey charts from US Lake Survey 1875; aerial photography from US Army Corps of Engineers 1974

HISTORICAL DEVELOPMENT

The shoreline configuration of the coastal area surrounding the present-day inlet of the West Branch of Twelvemile Creek has undergone numerous changes since the early nineteenth century. The data come from analysis of maps and aerial photographs.

Sequential Changes

Before the turn of the century, the coastline at the present-day inlet of the West Branch of Twelvemile Creek was straight and uninterrupted. An Old Holland Land Purchase map dated 1823 indicates that the entire Twelvemile Creek once entered Lake Ontario through a single inlet at Tuscarora Bay (Figure 6). The accuracy of these maps is uncertain; however, those of the latter nineteenth century indicate a similar shoreline configuration to the Old Holland Land Purchase Survey, assuming a notable amount of bluff/shoreline recession over the years.

Sometime in the 1830s, timber crib jetties were built at the inlet of Twelvemile Creek (present-day East Branch) at Wilson Harbor (J. Pope, personal communication, 1978). A federal project adopted by Congress in 1873 provided for the dredging of the channel between the jetties to a depth of 3.7 m (12 ft).

By 1876, sheet metal pilings reinforced the jetties and a channel 30.5 m (100 ft) wide and 3.7 m (12 ft) deep was secured. The jetties were extended from time to time; in 1884 the west jetty was 259 m (850 ft) long and the east jetty 227 m (745 ft). Shore protection structures extending 61 m (200 ft) west and 110 m (360 ft) east from the jetties were constructed in 1882 and 1889 respectively. None of the original shore protection structures remain today.

By 1902, the bluffs had eroded back so far that a breach of Twelvemile Creek occurred just west of the area where it entered Tuscarora Bay.

This allowed the western tributaries of Twelvemile Creek (then called Tuscarora River) to become separate and to discharge directly into Lake Ontario, leaving the peninsula known as The Island. The West Branch of Twelvemile Creek then discharged into Lake Ontario 1.4 km (0.9 mi) west of Wilson Harbor and a bar formed across the former Tuscarora River channel at the western end of Tuscarora Bay. In 1905, the federal government abandoned the improvement and reconstruction plan of the late 1800s, leaving all structures open to ruin and destruction.

Aerial photographs taken in 1938 show that the placement of both inlets had not changed significantly since 1902, but that the bluffs had receded greatly in that time. In 1938, the channel at Wilson Harbor had a reported depth of 0.6 m or 2 ft (US Congress 1940) and the Chief of Engineers recommended reconstruction of the jetties and restoration of the channel. The water of Tuscarora Bay, used extensively for boating and residential purposes, became stagnant, was polluted by sewage from the surrounding cottages, and overgrown in shallow areas with various aquatic flora (US Congress 1940).

By this time, several small groins (shore-protecting structures) and boat landings had been built at the privately owned beaches just west of the mouth of the West Branch and along The Island. None of these structures remain today. At the time, they protected the small narrow beaches by trapping longshore drift and aided in stabilizing the shoreline to a limited extent. The west jetty at Wilson Harbor trapped sufficient drifting sand to create a single beach up to 23 m (75 ft) wide for 0.4 km (0.25 mi) westward.

Further improvements of the Tuscarora State Park coastline were proposed by Congress in 1943. These included the placement of three groins reinforced with sand fills along the beach and a sand fill at the back and western end of Tuscarora Bay to a height of 2.4 m (8 ft) above datum level. Congress rejected both proposals (US Congress 1943).

Since then, aerial photography and topographic maps show little change in the coastal area, with the exception of continued shoreline recession. The present shoreline is virtually unprotected and rapidly eroding at a constant rate. The only current maintenance efforts are annual dredging of the inlet by the US Army Corps of Engineers and privately controlled dredging in Wilson Harbor.

Recession Rates

Since 1875, the coastline of Niagara County has been receding at an average long-term rate of 0.46 m/yr (1.5 ft/yr). The short-term recession rate is 0.79 m/yr or 2.6 ft/yr (Drexhage and Calkin 1981). Recession rates of the immediate coastal area surrounding the West Branch of Twelvemile Creek are much higher than these general figures. The highest short-term rate for the entire county measured since 1938 was at the till bluff just west of the West Branch. This was 2.1 m/yr (6.9 ft/yr).

Since erosional losses appear to be episodic, large amounts of recession often take place during relatively short periods of time with the increase related to changing lake levels.

Recession rates have been calculated by comparing air photographs and maps. The period between 1938 and 1951 had the highest rate of recession at 1.8 m/yr (5.9 ft/yr). The time period between 1955 and 1973 had a lower mean recession rate than that calculated for the past century, 1.0 m/yr (3.2 ft/yr), and this period also had lower than average lake levels.

The high recession rates in the area of the west bluffs adjacent to the inlet may be due largely to the fact that these bluffs have remained unprotected from wave attack throughout the period of record (since 1875). Composition and nature of the bluffs also have significant influence. The highest recession rates occur during periods of higher than normal lake levels in conjunction with stormy periods.

SEDIMENT TRANSPORT AND DEPOSITION

We collected 23 representative sediment samples from the beach, bluff, and nearshore environments of the study area on 15 July 1977, and 11 samples from along the whole creek bed on 8 April 1978. Pebble counts were carried out twice within the period of field investigation; the first time 29 July 1977 and the second 3 May 1978. We analyzed all samples by standard laboratory and statistical techniques (Krumbein and Pettijohn 1938; Rittenhouse 1943; Imbrie and Van Andel 1964; Griffiths 1967) in order to determine both textural and lithologic properties.

Following is a discussion of sediment size and shape, composition and texture, wave processes, and the roles each play in sediment transport at the West Branch.

Size and Shape Analysis

A size and shape analysis of sediment helps to determine the source area of transported sediment (Griffiths 1967). Since sediment particles are sorted according to size, this factor determines how and where the sediment is transported. High energy areas that are characterized by constructive waves, or waves that add rather than remove sediment, produce beaches with coarse sediment deposited farther upslope. Finer sediments that require less energy to transport are carried up the beach and back down again to be deposited closer to the low-tide mark. Coarse sediment deposits are usually found closer to the source of transport because heavy materials often settle out of the water first.

To distinguish a general trend of direction as related to increasing sediment size, we used TREND (Miller 1956). TREND is a computer program to interpret size data that have been plotted as map coordinates. In the case of Twelvemile Creek sediments, samples are taken from beaches and nearshore areas in the inlet. This area extends 15.2 m (50 ft) past each of the boundaries of the Central Reach.

The TREND study shows that sediment size decreases eastward and lakeward across the West Branch of the Twelvemile Creek inlet. This follows the general rule of longshore drift size sorting and indicates that in the confines of the study area, most of the sediment comes from the bluffs of the Western Reach (Johnson 1953).

Lithological Analysis

A lithological analysis determines the composition of sediment comprising beaches, the abundance of different minerals, and can be used to locate the source of the particles. For the Twelvemile Creek study a pebble count technique was used. For each location, 100 pebbles within a square foot area, between 30 and 100 mm (1.2 and 3.9 in) in diameter, were counted. The lithology of the sand-sized sediments was analyzed by inspecting the heavy minerals in the various size ranges.

Pebble counts of the entire area show almost identical lithologic composition. There is a dominance of red shale and sandstone of the Queenston Formation derived from both till bluffs and bedrock outcrops. However, the areas of coarser particles contain greater amounts of igneous and metamorphic rocks. These are derived from erosion of the till and are the most resistant lithologic types here. Since the west spit has slightly greater amounts of the coarse pebbles, it also has slightly greater percentages of igneous and metamorphic rock types. The heavy mineral analyses also yielded little information about source, but the presense of easily weathered minerals in relatively large quantities suggests that erosion of the nearby till bluffs was also an important source of the sand-sized sediment.

Fluorescent Tracer Study

The primary cause of sediment movement along the coastline is longshore transport combined with the agitating action of the breaking waves (Johnson 1953; Scott 1954). Up to 80 percent of all material moved by wave action is found in the area shoreward of the breaking point. Furthermore, Johnson (1953) has shown that longshore transport is characterized by summer waves of intermediate-to-low steepness.

To substantiate the effects of summer waves and longshore transport, a fluorescent tracer study was carried out during the week of 29 August to 5 September 1977. The study was also an attempt to observe the movement patterns of sediment like that of the inlet. Sediment used as tracer material was taken from the dredge spoils of inlet dredging of 1 July 1977 in an attempt to copy the type of sediment found in the littoral zone of the study area (Table 1).

Ninety-one kilograms (200 lb) of sediment were collected and divided into three groups after all sand and finer-than-sand particles had been sifted out. Each group was painted either yellow, green, or orange (Jolliffe 1964). The amount and sizes of tracers used in the study are listed in Table 2. The sediment was then introduced into the littoral zone in 4.5 kg (10 lb) amounts, just before dredging operations began (Figure 7).

We sampled at about 8 am everyday for one week. The nearshore zone was sampled on a grid of 3 m (10 ft) dimension, starting 3 m (10 ft) west of the westerly placed (green) stones and ending 3 m (10 ft) east of the easterly placed (yellow) tracers, and extending from the coast to 24.4 m (80 ft) offshore. At each grid intersection point, we counted and noted the number of tracer pebbles seen there (Jolliffe 1964; Ingle 1966; Coakley 1970).

Based on the tracer pebble project, the predominant direction of the dispersion during the sample period, 29 August through 5 September 1977, was westward and movement occurred entirely within the breaker zone. At the end of the week period, the majority of the westerly placed tracers showed a general trend of movement complementary with the daily wave climate and resulted in the accumulation of these pebbles in the inlet area. Wind and wave data were taken during the week; wind velocity and direction with accompanying wave direction, height, and period were measured every two hours.

The larger tracer pebbles moved shoreward and were dispersed westward more rapidly than the smaller stones, particularly as wave energy increased with increasing wave height (Jolliffe 1964).

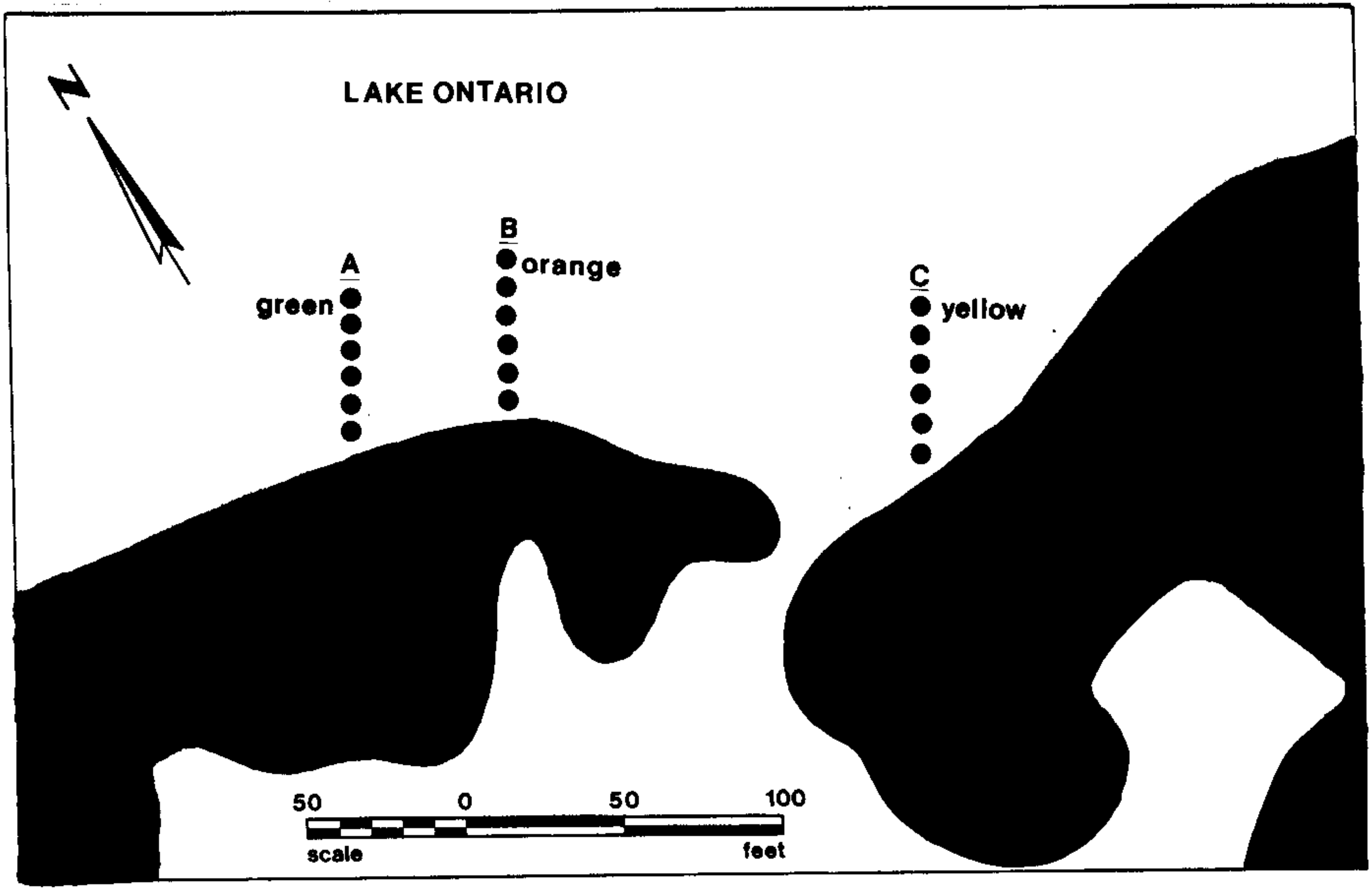

Figure 7 Approximate Placement of Tracer Pebbles into Littoral Zone

TABLE 1

Dredging Record for Field Period April 1977-June 1978

Date	Amount dredged m^3	(yd^3)
30 June-1 July 1977	5,168	(6,760)
29 August 1977	3,636	(4,755)
10 April 1978	4,002	(5,234)
TOTAL	12,806	(16,749)

TABLE 2

Classification of Tracer Pebbles

Pebble size mm (in)	Color	Approximate # of each size
50.8-76.2 (2-3)	Orange	200 stones
50.8-76.2 (2-3)	Green	200 stones
50.8-76.2 (2-3)	Yellow	150 stones
25.4-50.8 (1-2)	Orange	550 stones
25.4-50.8 (1-2)	Green	600 stones
25.4-50.8 (1-2)	Yellow	400 stones
less than 25.4 (less than 1)	Orange	600 stones
less than 25.4 (less than 1)	Green	600 stones
less than 25.4 (less than 1)	Yellow	500 stones

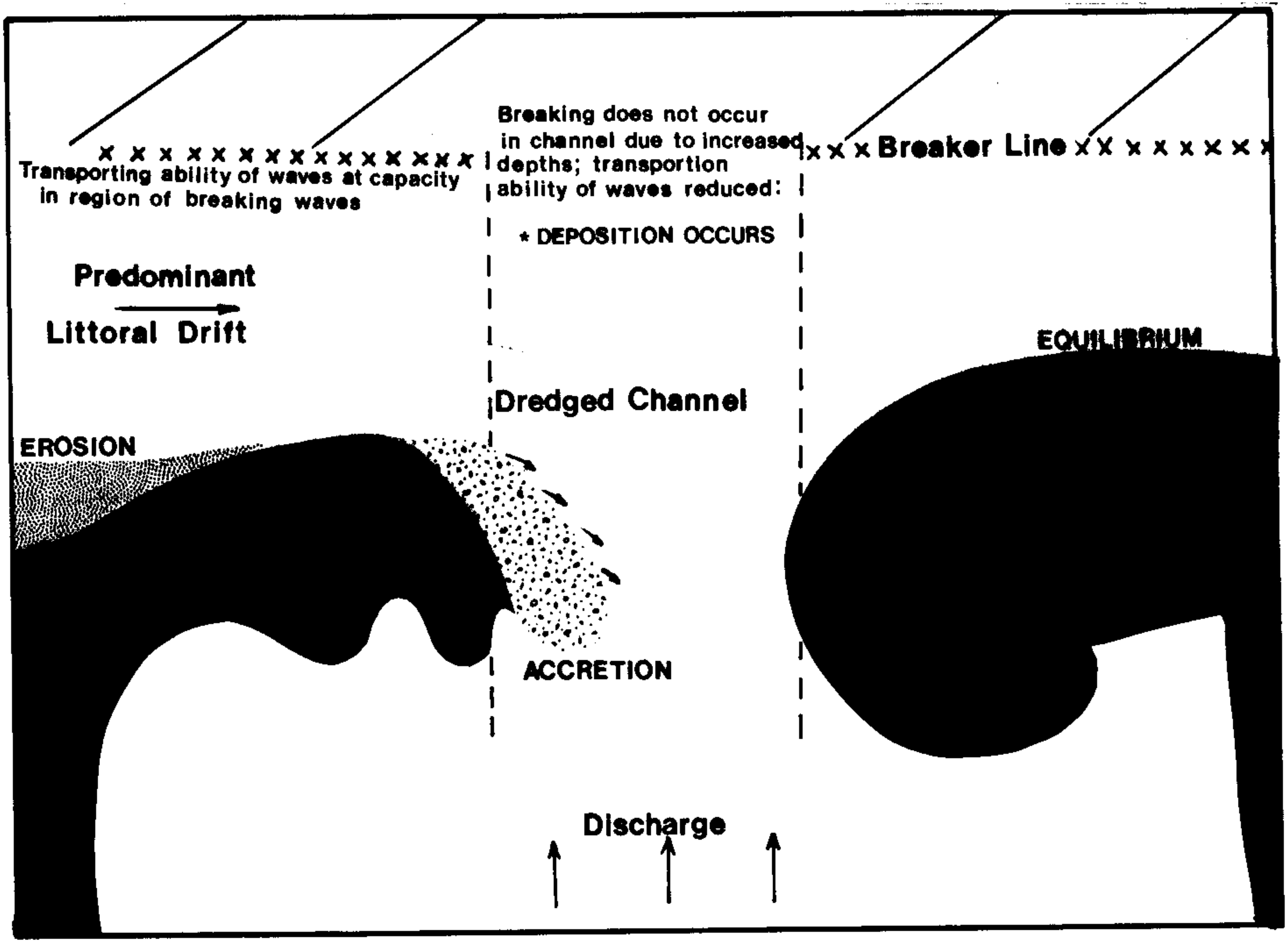

Figure 8 Sediment Accumulation in Dredged Channel

Several months later, after winter storm conditions and ice had come and gone, tracer pebbles were spotted at various locations across the inlet coastal area. The yellow tracer placed to the east of the inlet was carried farther east and did not accumulate in the inlet area. The sediment used in the tracer study showed a tendency to accumulate at the inlet area rather than be transported in the direction of presumed normal longshore drift.

Dredging

Coastal inlets in their natural state, or improved to meet navigational requirements, often interrupt normal longshore transport (Coastal Engineering Research Center 1973; Jolliffe 1974). When dredged, littoral materials accumulate as greater than normal amounts of sediment deposits in the dredged channels (Coastal Engineering Research Center 1973). Measurements of sediment movement versus wave conditions through tracer studies indicate that most of the longshore transport of material occurs in the vicinity of breaking waves (Ingle 1966; Coakley 1970; Jolliffe 1961). Here, the available energy is converted suddenly from the sloshing back and forth motion of passing waves into turbulence (Colonell and Goldsmith 1971). For that portion of the wave that moves over a dredged channel, breaking does not occur because of the increased depth. The wave energy, passing the normal point of breaking, is spread out by refraction, and is scattered. Therefore, the degree of turbulence is insufficient to transport material across the channel and sediment accumulates there (Figure 8).

To maintain a navigable channel in the West Branch of Twelvemile Creek inlet, the accumulated littoral sediment must be dredged periodically. As previously explained, the West Branch of Twelvemile Creek did not have sufficient capacity or competence to interfere with the accumulative sediment processes. Table 1 shows the date of each dredging operation throughout the period of the field investigation, and the amount of material removed from the inlet each time. Total sediment removal for the field year was 12,806 m^3 (16,749 yd^3). For the past 20 years, dredging operations have continued at the inlet in a similar way.

SEDIMENT BUDGET

The sediment budget is based on sediment removal, transportation of sediment, and its deposition, causing excesses or deficiencies of the quantity of material. In the study area, the principal natural sources of beach sediment are erosion of bluffs and beaches, and river transported sediments. Inlets, estuaries, and deep offshore areas are sinks, or areas where sediment is deposited.

These estimates assume prevailing longshore drift is to the east. They are based on long-term bluff erosion measurements of Drexhage and Calkin (1981) and field measurements made during this study in 1977 and 1978.

Western Reach

To determine the amount of sediment entering the Central Reach from the Western Reach, one estimates the volume of sediment transported along the entire coast to the west. The amount entering the Western Reach from the area as far west as the Niagara River is 24,422 m^3/yr (31,944 yd^3/yr). When the amount of sediment is added to the longshore transport system exclusively from the Western Reach, the amount becomes 28,058 m^3/yr (36,700 yd^3/yr) because much sediment is lost to the lake.

Central Reach

For 1977-78, 12,805 m^3 (16,749 yd^3) of sediment were removed by dredging from the mouth of the inlet at the West Branch of Twelvemile Creek. This is similar to amounts dredged in previous years (US Army Corps of Engineers, personal communication, 1977; R. Klein, personal communication, 1977). The amount of sediment entering the Eastern Reach from the Central Reach is 15,869 m^3/yr (20,757 yd^3/yr). This takes into account the amount of river load remaining in the inlet or lost to the lake.

This amount is only slightly more than half the amount of longshore drift moved into the Central Reach from the Western Reach. Therefore, this implies that almost half the sediment in longshore drift deposits at the inlet or contributes to spit growth.

Eastern Reach

Approximately 17,888 m^3/yr (23,397 yd^3/yr) of material leaves the eastern boundary of the Eastern Reach. Much of this sediment is subsequently trapped by the jetties at Wilson Harbor. Evidence contributing to this conclusion is an accumulating sand-pebble-cobble beach building up on the western side of the west jetty at Wilson Harbor.

Summary

Approximately 24,422 m^3/yr (31,944 yd^3/yr) enter the study area as far west as the Niagara River. An additional 3,636 m^3 (4,756 yd^3) is added to this figure from the Western Reach showing that 28,058 m^3 (36,700 yd^3) enter the Central Reach. From this amount, 12,189 m^3 (15,943 yd^3) are deposited in the Central Reach and the remaining 15,869 m^3 (20,757 yd^3) enter the Eastern Reach. From the Eastern Reach, another 2,018 m^3 (2,640 yd^3) of sediment are added to the drift for a total of 17,888 m^3 (23,397 yd^3) of sediment annually leaving the Eastern Reach or being trapped by the jetties of Wilson Harbor.

COMPUTING THE SEDIMENT BUDGET

To compute the sediment budget by methods outlined by the Coastal Engineering Research Center (1973, p. 4-124 through 4-139) several elements must be defined. These subscripted elements of a sediment budget are identified in Table 3.

Elements make either a point (Q) or line (q) contribution to the littoral zone according to the size of the boundary across which the sediment enters or leaves. To make a point (Q) source or sink contribution, the sediment must be respectively added or subtracted across a limited boundary. An example of a limited boundary is the entrance of a river into an inlet. To make a line source or sink, the sediment is added or subtracted over a large boundary such as happens during storm washover of the coastline. Such boundaries are detailed in Table 3.

Using the following table the subscripted elements for the equation can be identified:

TABLE 3

Subscripted Elements for Sediment Budget

Location of source or sink	Offshore side of littoral zone	Onshore side of littoral zone	Within littoral zone	Longshore ends of littoral zone
Point source (yd^3/yr)	Q_1^+ Offshore shoal or island	Q_2^+ Rivers, streams	Q_3^+ Replenishment	Q_4^+ Longshore transport in
Point sink (yd^3/yr)	Q_1^- Submarine canyon	Q_2^- Inlets	Q_3^- Mining, extractive dredging	Q_4^- Longshore transport out
Line source ($yd^3/yr/ft$ of beach)	q_1^+ Sand transport from the offshore	q_2^+ Coastal erosion including erosion of dunes and cliffs	q_3^+ Beach erosion; calcium carbonate production	
Line sink ($yd^3/yr/ft$ of beach)	q_1^- Sand transport to the offshore	q_2^- Overwash; coastal land and dune storage	q_3^- Beach storage; calcium carbonate losses	

Source: Coastal Engineering Research Center 1973

The total sediment budget is shown as follows:

$$\sum_{i=1}^{4} Q_i^{+} \sum_{i=1}^{4} Q_{i-}^{*+} \left(\sum_{i=1}^{3} Q_i^{-} \sum_{i=1}^{3} Q_i^{*-} \right) = 0$$

where: Q_i is a point source

Q_i^{-} is a point sink

Q_i^{*+} is a line source

Q_i^{*-} is a line sink,

and:

$$Q_i^{*} = b\ q$$

where: b_i is the length of shoreline over which a line source is active

q_i is the line source or sink within a given volume boundary

The subscripts i equals 1, 2, 3, or 4 corresponding to the subscripts of Table 3.

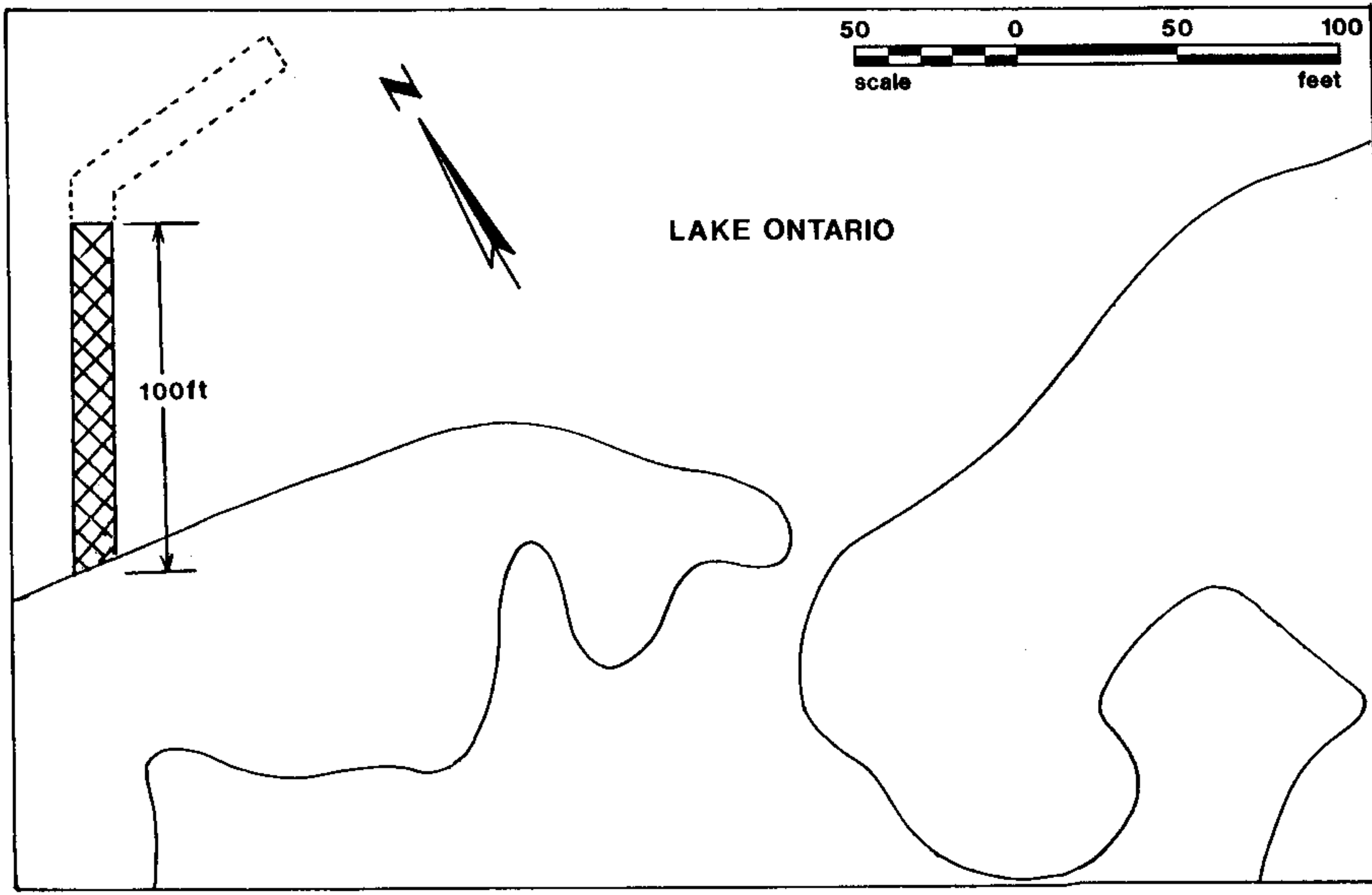

Figure 9 Proposed Placement of Jetty off West Bank of West Branch, Twelvemile Creek

SOLUTIONS

Since the sediment budget suggests that a greater amount of sediment is entering the inlet area than is being transported out, the principal concern should be to even out these ratios so that the coastline at the inlet will be in near equilibrium. Ideally, the amount of sediment entering the inlet compartment should be as equal as possible to the amount leaving.

One possible solution is depicted in Figure 9. This involves building a jetty off the west bank of the creek, extending lakeward to the breaker zone, 15.2 to 30.5 m (50 to 100 ft) offshore. The construction of a jetty would prevent accumulation in the inlet by trapping the sediment entering the inlet compartment as longshore drift. It may also help prevent erosion of the western bluffs, thus partially cutting off a major sediment source.

GLOSSARY

Berm: the horizontal part of the beach or backshore formed by storm waves.

Escarpment: the steep face presented by the abrupt termination of stratified rocks (in this area, the northward-facing edge of the Lockport Formation).

Estuarine: of the area in which the lake and river waters mix.

Facies: a restricted part of a sediment layer that exhibits characteristics significantly different from those of other parts of the unit.

Fetch: the distance of open water over which wind blows to form waves; the longer the fetch, the higher the waves.

Fluvial sediment: sediment produced or transported by river action.

Formation: a unit of rock that has common characteristics such as lithology, that allows it to be mapped or distinguished over broad areas.

Gage record: the record of lake level fluctuations obtained by automatic recording equipment.

Groin: a man-made structure built to trap sediment.

Icefoot: a narrow fringe of ice attached to the coast and often thickened by frozen spray of waves.

Jetty: a man-made structure that keeps sediment from being deposited in a water region.

Lacustrine: of, or pertaining to lakes.

Lag deposit: coarse sediment left behind when finer particles blow or wash away.

Lithology: the physical character of rock.

Littoral: pertaining to the shore or nearshore zone, including the beach and wave washed portions offshore.

Longshore drift: movement of water and sediment parallel to and near the shoreline.

Queenston Formation: a succession of red sandstone and shale strata deposited in the Ordovician Period, about 440 million years ago.

Reach: a specified linear section of land or shoreline.

Recurved spit: a spit that forms a hook at its end.

Rip current: a seaward-moving streak of water that returns the water carried landward by waves.

Riprap: boulder-sized crushed rock used as fillers or barriers.

Saltation: transportation of particles in a current of wind or water, by movement through a series of bounces.

Seiche: very long waves sloshing back and forth between opposite shores.

Silt: fine-grained sediment particles between 0.62 and 0.0039 mm (0.002 and 0.00015 in) in diameter.

Slumping: material sliding down a slope.

Standing wave: two waves coming together and forming a wave of water that remains temporarily stationary.

Sublacustrine: beneath lake level.

Till: unsorted and unstratified sediment that is deposited by a glacier.

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